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A comparative study on various turbocharging approaches based on IC engine exhaust gas energy recovery

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HIGHLIGHTS

- Two novel turbocharging approaches of steam turbocharging and steam-assisted turbocharging were proposed.
- Steam turbocharging has higher energy saving potential than the other two turbocharging approaches.
- Steam turbocharging can achieve the target intake pressure in the entire IC engine speed area.
- Steam-assisted turbocharging can improve IC engine intake pressure at the low-speed operating conditions.

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ABSTRACT

In this paper, two kinds of novel boosting pressure approaches, steam turbocharging and steam-assisted turbocharging, have been proposed. And both are based on the principle of internal combustion (IC) engine exhaust gas energy recovery. In order to demonstrate the advantages of the two types of new turbocharging concepts, a comparative study among exhaust turbocharging, steam turbocharging and steam-assisted turbocharging was conducted on a passenger car gasoline engine, and the effects of various boosting pressure approaches on IC engine performances as well as turbocharging system energy flow were analyzed. The results show that, steam turbocharging can achieve the target intake pressure in the entire IC engine speed range, while steam-assisted turbocharging can improve IC engine intake pressure at the low-speed operating conditions; the energy saving potentials from high to low follow the subsequence of steam turbocharging, steam-assisted turbocharging and exhaust turbocharging; with the increasing of IC engine speed, the exhaust gas energy recovery efficiency of steam turbocharging system decreases and its maximum value is 6.5%, while the exhaust gas energy recovery efficiency of steam-assisted turbocharging and exhaust turbocharging first increases and then decreases.

1. Introduction

Recently, due to the increasingly severe problems of energy and environment, especially the petrol shortage and air pollution, more attention has been paid on the energy saving and environmental protection [1–3]. As the main consumer of fossil oil, the important power source of automobile and also the major source of air pollution, IC engine becomes the primary object for energy conservation and emission reduction in the world [4]. Under the circumstances, higher energy utilization efficiency and lower emissions are the two major development momentums for IC engine.

According to the analysis of IC engine energy balance [5,6], there are several kinds of approaches to improving the IC engine energy utilization efficiency, e.g., boosting pressure, exhaust gas energy recovery. On one hand, since the higher IC engine thermal efficiency appears in the higher load area, boosting pressure becomes one of the effective methods to improve IC engine thermal efficiency. As is well known, the first approach of boosting pressure on IC engine is mechanical supercharging [7]. A lot of research shows that mechanical supercharging could enhance IC engine power and torque under most of operating conditions. However, the improvement to IC engine thermal efficiency is very limited because part of IC engine effective work is consumed to drive the compressor. Another conventional approach of boosting pressure is exhaust turbocharging, which uses IC engine exhaust gas energy to drive the compressor through exhaust turbocharger [7]. In reality, exhaust turbocharging can be classified as a kind of means for exhaust gas energy recovery. Compared with mechanical supercharging engine, exhaust turbocharging engine has more advantages, e.g., higher thermal efficiency, for the compressor power comes from exhaust gas energy rather than IC engine

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Nomenclature

P	power (kW)
$\dot{m}$	mass flow rate (kg/s)
c_P	constant pressure specific heat (kJ/(kg K))
T	temperature (K)
p	pressure (kPa) (MPa)
ρ	density (kg/m^3)
k	adiabatic exponent
η	efficiency
V_s	displacement (l)
n	speed (r/min)
i	cylinder number
τ	stroke number
B	consumption of fuel (kg/s)
H_u	low heating value (kJ/kg)

Subscripts

exh	exhaust gas
com	compressor
int	intake gas
pum	pump
in	inlet
out	outlet
ste	steam
tur	turbine
wme	working medium
ere	exhaust gas energy recovery efficiency
ice	internal combustion engine
me	brake mean effective pressure
imp	improvement of thermal efficiency
tce	turbocharging engine
nae	naturally aspirated engine

Abbreviation

IC	internal combustion
ET	exhaust turbocharging
ST	steam turbocharging
SAT	steam-assisted turbocharging
BMEP	brake mean effective pressure
IMEP	indicated mean effective pressure
PMEP	pumping mean effective pressure
FMEP	friction mean effective pressure

effective work. However, studies indicate that exhaust turbocharging is also not the perfect method to promote the IC engine energy utilization efficiency [8,9], and one of the obvious defects is that it leads to a higher exhaust gas pressure. On the other hand, exhaust gas energy recovery is another approach to improving the total energy utilization efficiency of IC engine, which has been approved by lots of experts [10,11]. At present, an increasing number of scholars have concerned about this aspect. For example, He et al. [12] have proposed a combined thermodynamic cycle used for IC engine waste heat recovery; Dolz et al. [13] have studied the HD diesel engine equipped with a bottoming Rankine cycle as a waste heat recovery system; Liu et al. [14] have analyzed the recovery potentials of IC engine exhaust gas energy through Rankine steam cycle. Although lots of research has been conducted in the field of exhaust gas energy recovery and many concepts have been proposed, up to now, few approaches of exhaust gas energy recovery are used for IC engine boosting pressure except the exhaust turbocharging.

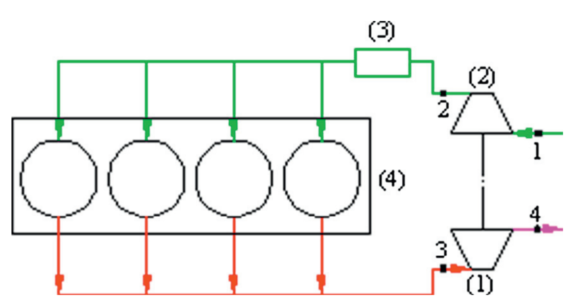
Since most of research on IC engine boosting pressure focused on the exhaust turbocharging, and the research on IC engine exhaust gas energy recovery mainly considered independent bottom cycle, the studies may be more interesting if the two kinds of research are combined together. In the previous study, we have proposed the concepts of steam turbocharging (ST) [15] and steam-assisted turbocharging (SAT), both of which are the new turbocharging approaches based on the principle of IC engine exhaust gas energy recovery. In this paper, a comparative study on various turbocharging approaches is conducted, for the purpose of revealing their energy saving potentials as well as the improvement to the IC engine performances.

2. Turbocharging approaches based on exhaust gas energy recovery

2.1. Exhaust turbocharging

Nowadays, exhaust turbocharging is the most prevalent approach of boosting pressure in the field of IC engine, and it is applied to almost any advanced IC engine [7,16]. Fig. 1 is the schematic diagram of IC engine exhaust turbocharging. As it shows, traditional exhaust turbocharging system consists of turbine, compressor and intercooler, etc. Among them, the turbine and the compressor are connected by a transmission shaft. Because the IC engine exhaust gas has a high temperature and high pressure (compared with ambient pressure), it still contains lots of energy which could be recovered by exhaust turbine. In the exhaust turbocharging system, exhaust gas is used as the working medium of turbine, while turbine acts as the power output device of boosting pressure system. During the exhaust gas expansion process, part of exhaust gas energy is recovered and transformed into useful work. Then, the useful work is used to drive the compressor.

In the light of the theory of IC engine exhaust gas energy recovery [9], exhaust turbocharging is a kind of direct method to reuse exhaust gas energy. Although the power of exhaust turbocharging comes from exhaust gas energy, IC engine exhaust process experiences the throttling loss in turbine and it results in a higher exhaust gas pressure. As a consequence, some of IC engine effective work should be consumed to overcome the additional exhaust gas pressure, and the improvement to the IC engine thermal efficiency by exhaust turbocharging is restrained.



(1) Turbine (2) Compressor (3) Intercooler (4) IC engine

Fig. 1. Schematic diagram of IC engine exhaust turbocharging.

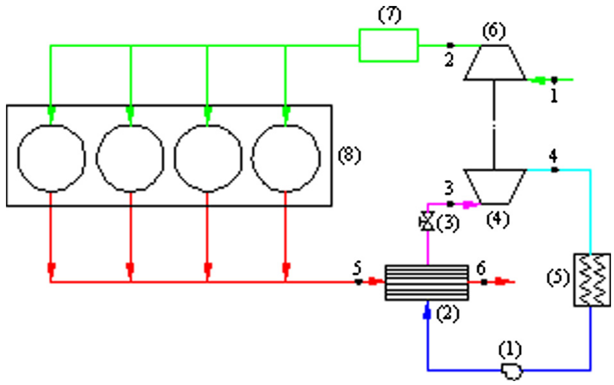


Fig. 2. Schematic diagram of IC engine steam turbocharging.

2.2. Steam turbocharging

In the previous study [15], the concept of steam turbocharging was proposed. Fig. 2 shows the schematic diagram of IC engine steam turbocharging. Being different from the exhaust turbocharging, a set of steam power cycle system [17,18] is coupled to IC engine exhaust pipe, which uses the high-temperature exhaust gas as the heat source of steam power cycle. In the steam turbocharging system, the "input energy" is from IC engine exhaust gas, while the "output work" is used to drive the compressor. As Fig. 2 illustrates, the steam turbocharging system consists of pump, heat exchanger, valve, turbine, condenser, compressor, etc. Among them, pump is used to control the cycle pressure; valve is used to adjust the flow rate of steam (or working medium water); heat exchanger is used to heat and evaporate the water; turbine is the power output equipment of the steam power cycle system, and condenser is used to condense the expanded steam for the next cycle. Similar to the exhaust turbocharging, the turbine and the compressor are linked by a transmission shaft.

In the steam turbocharging system, IC engine exhaust gas passes through the heat exchanger rather than the turbine. Because the pressure resistance in the heat exchanger is smaller than that in the turbine, exhaust gas pressure and exhaust process work of steam turbocharging engine are less than those of exhaust turbocharging engine. Therefore, the energy utilization efficiency of steam turbocharging engine could have an increase over the exhaust turbocharging engine.

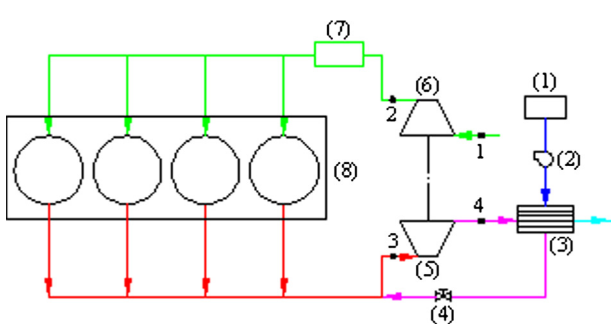


Fig. 3. Schematic diagram of IC engine steam-assisted turbocharging.

2.3. Steam-assisted turbocharging

Combining the characteristics of exhaust turbocharging and steam turbocharging together, the concept of steam-assisted turbocharging is proposed. Similar to the steam turbocharging, it is also a novel boosting pressure approach based on the principle of IC engine exhaust gas energy recovery. The schematic diagram of IC engine steam-assisted turbocharging is depicted in Fig. 3. As shown in this figure, steam-assisted turbocharging consists of an open steam power cycle system [18] and an IC engine exhaust turbocharging system. The open steam power cycle system is coupled to IC engine exhaust pipe, and it uses IC engine exhaust gas energy to produce steam. Then, the steam is injected into the turbine inlet, thus it can be used as a complementary working medium for the turbine. In this way, the turbine can have a higher efficiency and higher output power since the mass flow rate of turbine working medium is increased. As a matter of fact, steam-assisted turbocharging can be regarded as an improvement scheme of exhaust turbocharging.

2.4. Comparison of various turbocharging approaches

All the boosting pressure approaches mentioned above are based on the principle of IC engine exhaust gas energy recovery. Among them, exhaust turbocharging is a "pressure-based" method for IC engine exhaust gas energy recovery. In the exhaust turbocharging system, IC engine exhaust gas is used as the direct working medium of turbine. In general, exhaust turbocharging system is relatively simple and the applied technology is very mature. However, there are still some defects, e.g., the higher IC engine exhaust gas pressure, the bad working performances at low-speed operating conditions.

Steam turbocharging is a "heat transfer based" method for IC engine exhaust gas energy recovery. As it recovers IC engine exhaust gas energy through heat transfer and thermodynamic cycle, rather than exhaust gas direct expansion, steam turbocharging system has little negative influence on IC engine exhaust gas process. Additionally, the operating parameters of steam turbocharging, such as steam pressure and flow rate, are independent of IC engine working cycle. As a result, the turbine and compressor may have expected working performances even at low-speed operating conditions. However, a set of steam power cycle system is required, which means more components and higher cost than exhaust turbocharging system.

Steam-assisted turbocharging is a transition mode between exhaust turbocharging and steam turbocharging. It has integrated the advantages of both the two kinds of boosting pressure approaches. Correspondingly, in the steam-assisted turbocharging system, IC engine exhaust gas energy is recovered from both the exhaust gas expansion and the heat transfer (steam power cycle). Compared with the exhaust turbocharging, steam-assisted turbocharging can further improve the IC engine intake gas pressure especially at the low-speed operating conditions. However, the effective working range depends on IC engine target boosting pressure. Moreover, a set of steam generating plant is required, which results in higher system cost.

3. Matching and calculating of various turbocharging systems

3.1. Calculation formulas for various turbocharging systems

Since all the boosting pressure approaches discussed in this paper are based on IC engine exhaust gas energy recovery, firstly, the calculation formula for IC engine exhaust gas energy is given as [19]

$$P_{exh} = \dot{m}_{exh} \cdot (c_{P,exh} \cdot T_{exh} - c_{P,0} \cdot T_0) \tag{1}$$

where P_{exh} is the IC engine exhaust gas energy flow; $\dot{m}_{exh}$ is the mass flow rate of exhaust gas; $c_{P,exh}$ is the constant pressure specific heat of exhaust gas at the inlet of turbine (or heat exchanger); T_{exh} is the exhaust gas temperature at the inlet of turbine (or heat exchanger); $c_{P,0}$ is the constant pressure specific heat of exhaust gas at the ambient temperature; T_0 is the ambient temperature.

The required compressor power can be calculated according to the following formula:

$$P_{com} = \dot{m}_{\text{int}} \cdot c_{P,1} \cdot T_1 \cdot \left(\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right) \bigg/ \eta_{com} \tag{2}$$

where P_{com} is the required compressor power; $\dot{m}_{\text{int}}$ is the mass flow rate of intake gas; $c_{P,1}$ is the constant pressure specific heat of intake gas at the compressor inlet; T_1 is the intake gas temperature at the compressor inlet; p_1 is the intake gas pressure at the compressor inlet; p_2 is the intake gas pressure at the compressor outlet; κ is the isentropic exponent; η_{com} is the isentropic efficiency of compressor.

In the steam turbocharging system and steam-assisted turbocharging system, the pump consumes effective power, the calculation formula of which is written as:

$$P_{pum} = \frac{p_{out} - p_{in}}{\rho} \cdot \frac{\dot{m}_{ste}}{\eta_{pum}} \tag{3}$$

where P_{pum} is the effective power consumed by pump; $\dot{m}_{ste}$ is the mass flow rate of steam (or water); p_{in} and p_{out} are the pressure of working medium at the inlet and outlet of pump, respectively; ρ is the density of working medium; η_{pum} is the isentropic efficiency of pump.

In these turbocharging systems, the output power of turbine can be calculated as:

$$P_{tur} = \dot{m}_{wme} \cdot c_{P,3} \cdot T_3 \cdot \left(1 - \left(\frac{p_4}{p_3} \right)^{\frac{k-1}{k}} \right) \cdot \eta_{tur} \tag{4}$$

where P_{tur} is the output power of the turbine; $\dot{m}_{wme}$ is the mass flow rate of turbine working medium (exhaust gas or steam); $c_{P,3}$ is the constant pressure specific heat of working medium at the turbine inlet; T_3 is the working medium temperature at the turbine inlet; p_3 is the working medium pressure at the turbine inlet; p_4 is the working medium pressure at the turbine outlet; η_{tur} is the isentropic efficiency of the turbine.

To better evaluate the utilization efficiency of exhaust gas energy, the exhaust gas energy recovery efficiency of turbocharging system is defined, and its mathematical expression is given as:

$$\eta_{ere} = \frac{P_{tur}}{P_{exh}} = \frac{P_{tur}}{\dot{m}_{exh} \cdot (c_{P,exh} \cdot T_{exh} - c_{P,0} \cdot T_0)} \tag{5}$$

where η_{ere} is the exhaust gas energy recovery efficiency of turbocharging system.

The calculation formula for the effective power of IC engine is given as:

$$P_{ice} = \frac{p_{me} \cdot V_s \cdot n \cdot i}{30\tau} \tag{6}$$

where P_{ice} is the effective power of IC engine; P_{me} is the brake mean effective pressure (BMEP) of IC engine; V_s is the displacement of each cylinder; n is the IC engine speed; i is the cylinder number; τ is the stroke number.

As an important parameter for IC engine economic performance, the effective thermal efficiency of IC engine can be calculated as

$$\eta_{ice} = \frac{3.6 \times 10^3 P_{ice}}{B \cdot H_u} \tag{7}$$

where η_{ice} is the effective thermal efficiency of IC engine; B is the consumption of fuel; H_u is the low heating value of fuel.

In order to better evaluate the energy saving potential of these turbocharging approaches, the improvement to the IC engine thermal efficiency is defined as:

$$\eta_{imp} = \eta_{tce} - \eta_{nae} \tag{8}$$

where η_{imp} is the improvement to the IC engine thermal efficiency; η_{tce} is the thermal efficiency of the turbocharging engine; η_{nae} is the thermal efficiency of the naturally aspirated (NA) engine.

3.2. Matching and calculating of various turbocharging engines

A naturally aspirated gasoline engine was used in this study, and its basic parameters and specifications were listed in Table 1. Based on this gasoline engine, a comparative study of exhaust turbocharging, steam turbocharging and steam-assisted turbocharging was carried out. Above all, the corresponding numerical models for the three kinds of turbocharging engines were built by using the simulation software of GT-power. After that, the thermodynamic processes in both cylinders and turbocharging system could be simulated. Fig. 4 is the schematic diagram of GT-power model for the exhaust turbocharging engine.

For a gasoline engine, the suitable boosting pressure is relatively low, and it is usually lower than 2 bar. To better compare various turbocharging approaches and also to make the issue simpler, in this study the target boosting pressure of IC engine was set to 1.5 bar, and the operating conditions under full load were investigated in the entire IC engine speed range (from 1000 r/min to 5200 r/min). In the exhaust turbocharging model, the boosting pressure was controlled by the bypass-valve of turbine. Or rather, when the mass flow rate of exhaust gas is higher than a certain level, part of exhaust gas will be bypassed so as to maintain the fixed boosting pressure of 1.5 bar. During the calculation process of steam turbocharging, firstly, the required compressor power was reversely calculated according to the intake gas mass flow rate and target boosting pressure (1.5 bar), and then it was checked in accordance with the available exhaust gas energy as well as the output power of steam turbocharging system. At the same time, the boundary conditions of steam-assisted turbocharging, especially the effective working range, were determined by the calculation results of exhaust turbocharging model.

The design parameters of steam turbocharging system are listed in Table 2. As the table displays, various kinds of IC engine speed, steam pressure and steam temperature were considered in the entire IC engine speed range (from 1000 r/min to 5200 r/min) under full load. Table 3 gives the design parameters of steam-assisted turbocharging system. According to the calculation results of exhaust turbocharging engine, the effective working range of steam-assisted turbocharging was determined, which is between 1000 r/min and 2000 r/min. In this research, the speed points of 1000, 1250, 1500, 1750, 2000 r/min were discussed. Moreover,

Table 1
Basic parameters of gasoline engine (Naturally aspirated).

Item	Content
Engine type	Inline 4 cylinder, SI engine
Bore (mm)	66
Stroke (mm)	74
Displacement (l)	1.02
Compression ratio	9.5
Ignition mode	1–3–4–2
Rated power (kW)	43.6
Max torque (Nm)	82.8
Cooling type	Water-cooling

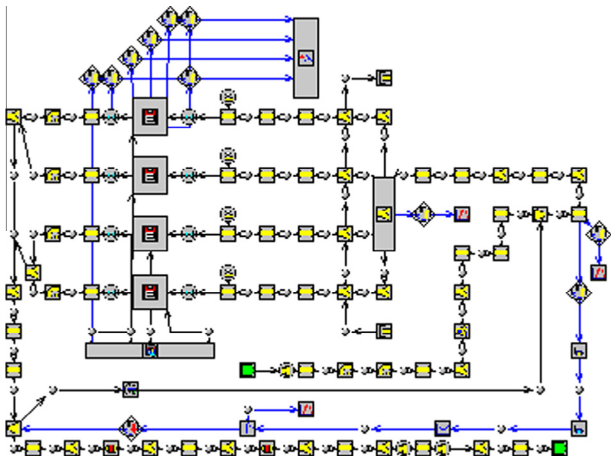


Fig. 4. Simulation model of exhaust turbocharging engine.

Table 2
Design parameters of steam turbocharging system.

Item	Content
IC engine speed (r/min)	1000, 2000, 3000, 4000, 5000, 5200
IC engine load	Full load
Steam pressure range (MPa)	0.2–2
Steam temperature (°C)	400, 500, 600, 700
Exhaust gas temperature at heat exchanger outlet (°C)	200
Turbine efficiency	0.65
Pump efficiency	0.85

Table 3
Design parameters of steam-assisted turbocharging system.

Item	Content
IC engine speed (r/min)	1000, 1250, 1500, 1750, 2000
IC engine load	Full load
Steam injection pressure (MPa)	0.5
Steam temperature (°C)	500
Exhaust gas temperature at the heat exchanger outlet (°C)	200

the steam injection pressure was set to 0.5 MPa, while the steam temperature was assumed to be 500 °C.

4. Results and discussions

4.1. Turbocharging system performances

Above all, the performances of exhaust turbocharging system are discussed. Fig. 5 shows the intake gas pressure of exhaust turbocharing engine at full load. As it illustrates, when the IC engine speed is higher than 2000 r/min, intake gas pressure of exhaust turbocharing engine can reach the target value of 1.5 bar. However, when the IC engine speed is lower than 2000 r/min, intake gas pressure of exhaust turbocharing engine is very low. Precisely, it is far below the target value. The reasons that boosting pressure at low-speed cannot achieve the target value are listed as follows. At low-speed operating conditions, IC engine exhaust gas pressure is too low, and it leads to a low expansion ratio in the turbine; in addition, exhaust gas mass flow rate and the corresponding turbine efficiency are very low; eventually, both of the two aspects result in the consequence that turbine output power of exhaust turbocharing engine is less than the required power of compressor. So as to achieve the target boosting pressure in the low-speed area (speed is between 1000 r/min and 2000 r/min) of exhaust turbocharing engine, steam-assisted turbocharging is applied. That is, when the speed of exhaust turbocharing engine is lower than 2000 r/min, steam-assisted turbocharging begins to work.

Fig. 6 demonstrates the turbine power of exhaust turbocharging system and steam-assisted turbocharging system. As can be seen from this figure, the turbine power of steam-assisted turbocharging system has a distinct increase over the exhaust turbocharging system. Compared with the exhaust turbocharing and the steam-assisted turbocharging, steam turbocharing is more complicated. As the working medium of steam turbocharing system is steam (or water) rather than IC engine exhaust gas, the operating parameters of steam turbocharing system have no direct relation with IC engine exhaust gas as well as IC engine working cycle. Accordingly, the steam pressure, steam temperature and mass flow rate are independent of IC engine exhaust gas, and all of them could be optimized or adjusted to achieve the expected turbine power. In this study, the steam pressure and steam temperature were set to independent variable, thus the steam mass flow rate could be calculated according to the energy balance equation. On this basis, the relationship among steam pressure, steam temperature and turbine power could be obtained, which is depicted in Fig. 7. In the meantime, the required compressor power for the target boosting pressure of 1.5 bar is also plotted in this figure, so as to better analyze the relationship between turbine power and compressor power.

As shown in Fig. 7(a–e), when the steam pressure is higher than a certain level, the turbine output power is greater than the required compressor power, and the rest of turbine power can be recovered by coupling a high-speed motor on the transmission shaft [15]. At each speed even low-speed, the turbine output power is far greater than the required compressor power. Therefore, in the entire IC engine speed range, steam turbocharing cannot only achieve the target boosting pressure of 1.5 bar, but also recover some additional effective power. Compared with the exhaust turbocharging and even the steam-assisted turbocharging, the steam turbocharging system has the largest turbine power. On the condition that exhaust gas energy is fixed, the higher the steam temperature is, the less the steam could be generated by the exhaust gas energy. However, higher steam temperature corresponds to higher cycle efficiency, and thus more effective power can be output through the turbine. In other words, higher steam temperature

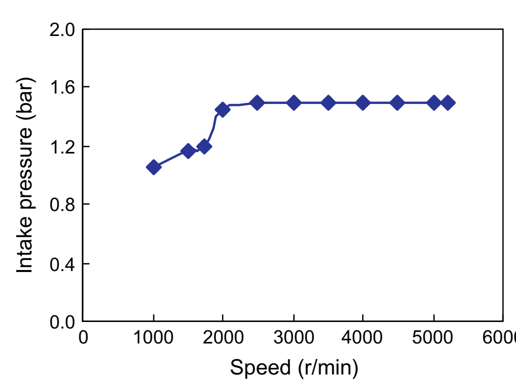


Fig. 5. Boosting pressure of exhaust turbocharging.

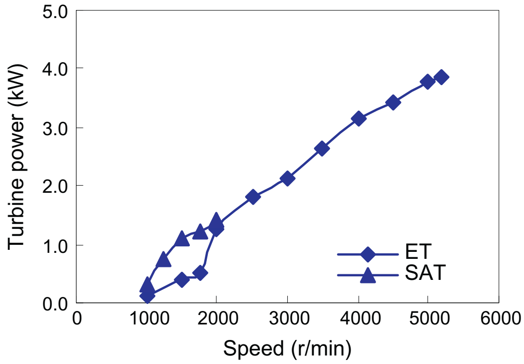


Fig. 6. Turbine power of exhaust turbocharging and SAT.

contributes to higher conversion efficiency of the exhaust gas energy (all that will be discussed in the next section).

4.2. Effects of various turbocharging approaches on IC engine performances

The greatest concern in this research is the effects of various turbocharging approaches on the IC engine performances especially the energy saving potentials. To discuss this issue, the performances of exhaust turbocharging engine, steam turbocharging engine and steam-assisted turbocharging engine should be compared and analyzed. Fig. 8 shows the intake gas pressure of various turbocharging engines under full load. As analyzed previously, the intake gas pressure of exhaust turbocharging (ET) engine can reach the target value of 1.5 bar only at the medium-speed and high-speed. With the steam-assisted turbocharging (SAT) applied, IC engine intake gas pressure has a significant improvement over the exhaust turbocharing engine. And the intake gas pressure of steam-assisted turbocharging engine is very approach to the target value of 1.5 bar except at the speed of 1000 r/min. However, thing is changed in the steam turbocharing (ST) engine. As Fig. 8 illustrates, the intake gas pressure of steam turbocharing engine can reach the target value of 1.5 bar in the entire IC engine speed range. From what is analyzed above, one can draw a conclusion that both the steam turbocharing and steam-assisted turbocharging can effectively promote the IC engine intake gas pressure at the low-speed operating conditions. According to the theory of IC engine [7], different intake gas pressure means different cylinder volumetric efficiency, and then different cylinder volumetric efficiency determines different brake mean effective pressure (BMEP) of gasoline engine. As shown in Fig. 9, in the entire IC engine speed range, the BMEP of steam turbocharging engine is much higher than that

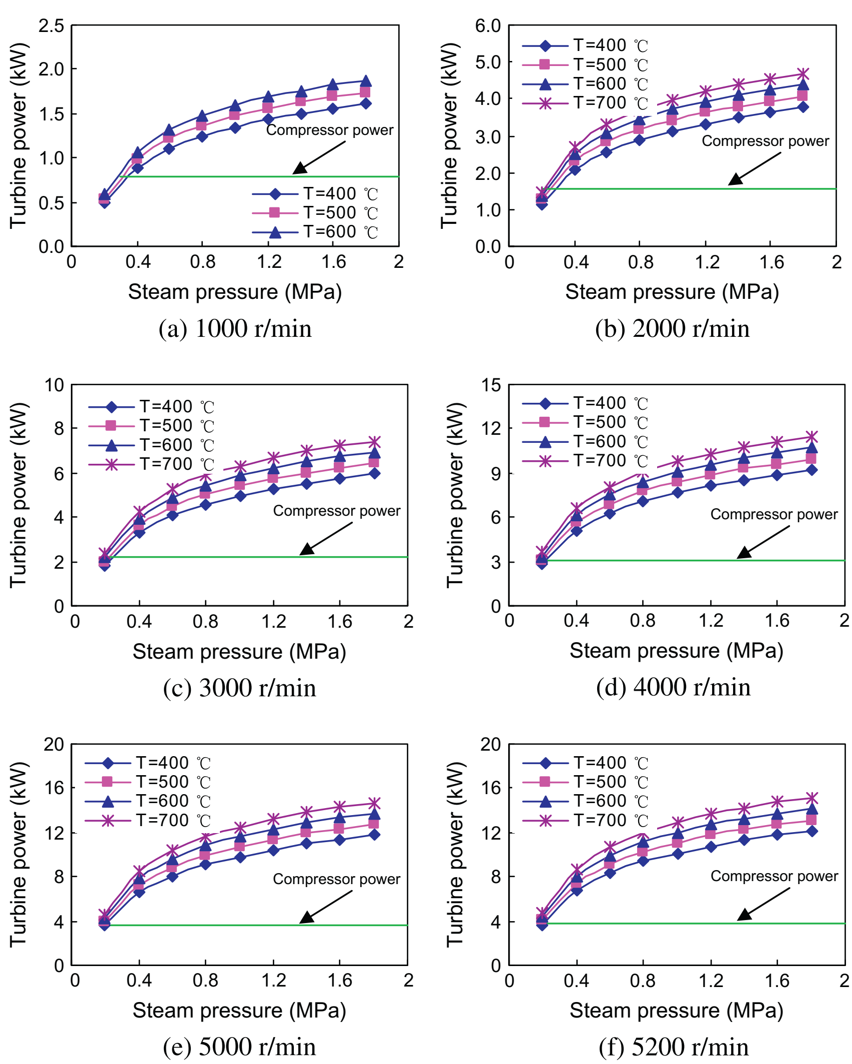


Fig. 7. Turbine power of steam turbocharging system.

of steam-assisted turbocharging engine and exhaust turbocharging engine. At the low-speed operating conditions, the BMEP of steam-assisted turbocharging engine has a significant improvement over the exhaust turbocharging engine due to the increasing of intake gas pressure.

As a fundamental parameter for IC engine power performance, the BMEP is analyzed in details. Firstly, the mathematical expression of IC engine BMEP can be written as:

$$\mathrm{BMEP} = \mathrm{IMEP} + \mathrm{PMEP} - \mathrm{FMEP} \tag{9}$$

where IMEP is the indicated mean effective pressure of IC engine. In gasoline engine, the IMEP is determined by IC engine intake gas (the mixture gas of fuel and fresh air) quantity. Since the intake gas quantity depends on cylinder volumetric efficiency, the IMEP is influenced by cylinder volumetric efficiency ultimately. PMEP is the pumping mean effective pressure of IC engine, which represents the pumping process work during the gas exchange process. And it is determined by both the IC engine intake gas pressure and exhaust gas pressure. FMEP is the friction mean effective pressure of IC engine, and it is mainly influenced by IC engine speed. When the IC engine speed is fixed, the FMEP can be approximately considered as a constant. It means that IC engine FMEP almost has no relation with the intake gas pressure as well as the boosting pressure approaches.

When the IC engine speed is higher than 2000 r/min, the intake gas pressure of steam turbocharging engine is the same as that of exhaust turbocharging engine. However, things are changed in the exhaust gas pressure. Compared with exhaust turbocharging engine, the exhaust gas pressure of steam turbocharging engine is reduced at each speed, while the exhaust gas pressure of steam-assisted turbocharging engine is increased, as shown in Fig. 10. It's worth mentioning that in Fig. 10 the position of exhaust gas pressure is point 3 in exhaust turbocharging (Fig. 1) and steam-assisted turbocharging (Fig. 3), but it is point 5 in steam turbocharging (Fig. 2). Since the exhaust gas pressure has a negative effect on the IC engine intake gas process during the valve overlap, the cylinder volumetric efficiency is influenced by the exhaust gas pressure, as shown in Fig. 11. Actually, the difference of volumetric efficiency between exhaust turbocharging engine and steam turbocharging engine is very small when IC engine speed is higher than 2000 r/min. With the steam-assisted turbocharging applied, both the intake gas pressure and the exhaust gas pressure are augmented. Compared with the exhaust gas pressure, the intake gas pressure plays a more important role in the volumetric efficiency. As Fig. 11 demonstrates, the volumetric efficiency of steam-assisted turbocharging engine has an increase over the exhaust turbocharing engine, but it still cannot reach the level of steam turbocharing engine. According to what is analyzed above, the following conclusions can be arrived. When the IC engine speed is higher than 2000 r/min, the IMEPs of exhaust turbocharging engine and steam turbocharging engine differ very unapparent since the differences in their volumetric efficiency are very slight. However, the evident differences in their exhaust gas pressure result in the large differences in their PMEP. Fig. 12 shows the PMEPs of three kinds of turbocharging engines. As it illustrates, the PMEP of steam turbocharing engine has an obvious improvement over the exhaust turbocharing engine since the exhaust gas pressure of the former is reduced. With the steam-assisted turbocharging applied, IC engine PMEP also has an increase on the basis of exhaust turbocharing engine owing to the increasing of intake gas pressure (as shown in Fig. 8). However, the improvement to the PMEP of steam-assisted turbocharging engine is restrained to a certain level due to the increasing of exhaust gas pressure (as shown in Fig. 10).

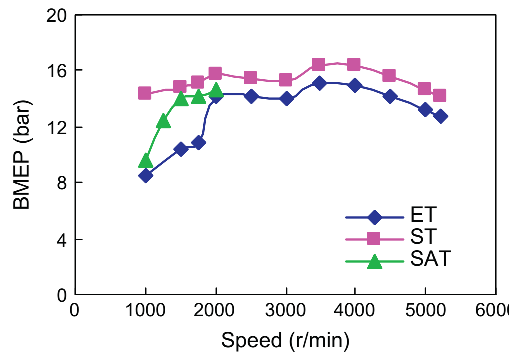


Fig. 9. Comparison of IC engine BMEP.

As one of the most paramount parameters for IC engine performance, the effective power of various turbocharging engines is discussed, and the result is depicted in Fig. 13. As the figure illustrates, both the steam turbocharging and steam-assisted turbocharging can effectively improve the IC engine effective power. Nevertheless, the effective power of steam-assisted turbocharging engine is a bit lower than that of steam turbocharging engine. Lastly, the effective thermal efficiency of various turbocharging engines is discussed. Fig. 14 shows the effective thermal efficiency of original naturally aspirated (NA) engine, exhaust turbocharging engine, steam turbocharging engine and steam-assisted turbocharging engine. Since the intake gas pressure and the BMEP are increased, the effective thermal efficiency of three kinds of turbocharging engines is boosted over the original naturally aspirated engine at most of IC engine speed. However, the improvement potentials of various turbocharging approaches are different from each other. Because the intake gas pressure is boosted without the increasing of exhaust gas pressure, the steam turbocharging engine has the highest

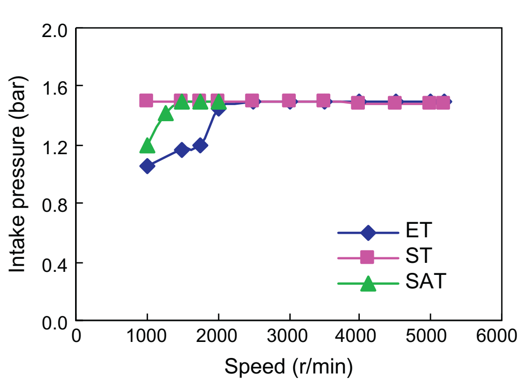


Fig. 8. Comparison of IC engine intake gas pressure.

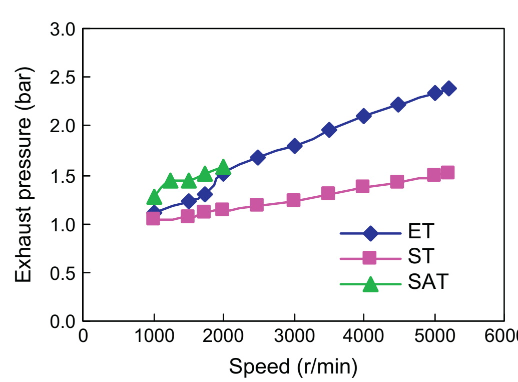


Fig. 10. Comparison of IC engine exhaust gas pressure.

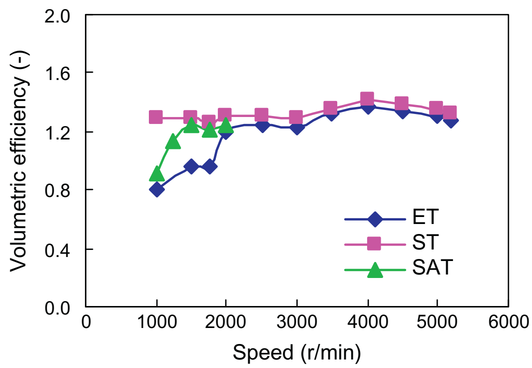


Fig. 11. Comparison of IC engine volumetric efficiency.

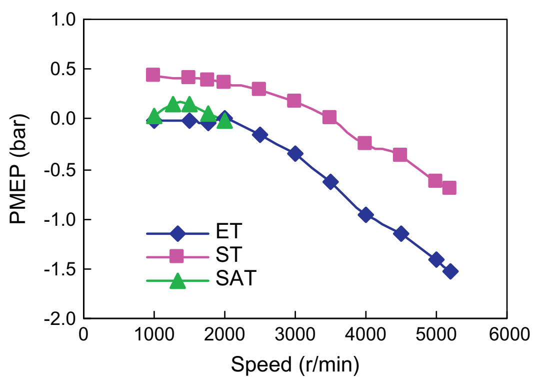


Fig. 12. omparison of IC engine PMEP.

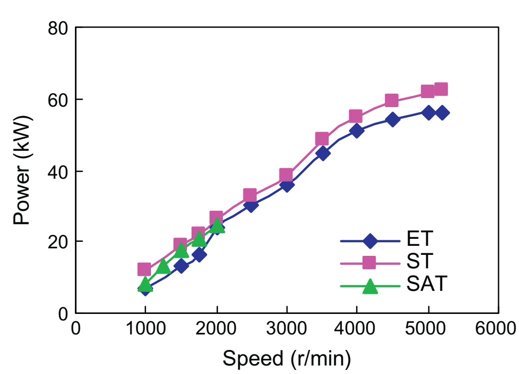


Fig. 13. Comparison of IC engine effective power.

thermal efficiency in the entire IC engine speed range. At the low-speed operating conditions, because of the low exhaust gas mass flow rate and the low turbocharger efficiency, the thermal efficiency of exhaust turbocharging engine is even lower than that of the original naturally aspirated engine, but this problem can be solved by the method of steam-assisted turbocharging. With the steam turbocharging applied, the maximum improvement to the IC engine effective thermal efficiency can reach 1.9% points over the exhaust turbocharging engine (at 5200 r/min). At the speed of 5000 r/min, the thermal efficiency of steam turbocharging engine has an increase of 3.6% points than the original naturally aspirated engine. With the steam-assisted turbocharging applied, the maximum improvement to the IC engine effective thermal efficiency is only 0.9% points on the basis of exhaust turbocharging engine (at 1500 r/min). Through the comparative analysis, one can

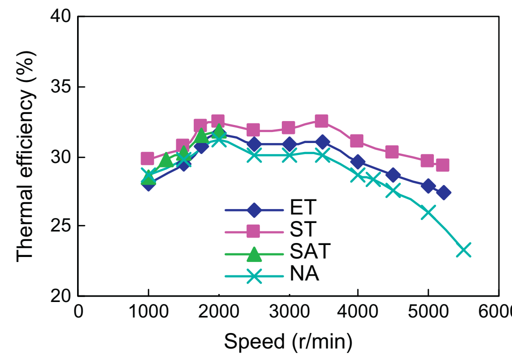


Fig. 14. Comparison of IC engine thermal efficiency.

draw a conclusion that steam turbocharging has the largest energy saving potential, followed by the steam-assisted turbocharging, and both of them have higher energy saving potential than the exhaust turbocharging. Moreover, steam-assisted turbocharging plays a more significant role in the IC engine power performance than the economic performance.

4.3. Energy recovery efficiency of various turbocharging approaches

As mentioned previously, exhaust turbocharging, steam turbocharging and steam-assisted turbocharging are based on the principle of exhaust gas energy recovery. Now, there comes the question that what is the recovery efficiency of exhaust gas energy of various turbocharging approaches. In order to answer this question, firstly, the exhaust gas energy of various turbocharging engines is discussed, and it is depicted in Fig. 15. As the figure shows, when the IC engine speed is higher than 2000 r/min, the exhaust gas energy of steam turbocharging engine and exhaust turbocharging engine are nearly the same. When the IC engine speed is lower than 2000 r/min, the exhaust gas energy of steam turbocharging engine is very close to that of steam-assisted turbocharging engine, and both of them are a bit higher than that of exhaust turbocharging engine. In a word, the exhaust gas energy of various turbocharging engines differs a little. Then, the next question is that how much exhaust gas energy is recovered for the purpose of boosting pressure? Fig. 16 describes the exhaust gas energy recovery efficiency of various turbocharging approaches. As it shows, when the IC engine speed is higher than 2000 r/min, the exhaust gas energy recovery efficiency of exhaust turbocharging and steam turbocharging are nearly identical, both of which decrease with the IC engine speed. This is because both the turbine output power and exhaust gas energy of exhaust turbocharging engine and steam turbocharging engine are almost the same. However, things are changed at the low-speed operating conditions. When the IC engine speed is lower than 2000 r/min, exhaust gas energy recovery efficiency of various turbocharging approaches is distinctive from each other due to the different turbine output power. Since the turbine output power of steam turbocharging engine can meet the requirement of target value (the required compressor power) at the low-speed operating conditions, steam turbocharging engine has the highest exhaust gas energy recovery efficiency, and its maximum value reaches 6.5% at 1000 r/min. Because the exhaust gas energy has reused through the method of steam-assisted turbocharging, the exhaust gas energy recovery efficiency of steam-assisted turbocharging has an increase over the exhaust turbocharging, while its maximum value is only 5.7%. In the meantime, exhaust turbocharging engine has the lowest exhaust gas energy recovery efficiency. This is because the turbine output power is constrained by several factors at low-speed operating conditions,

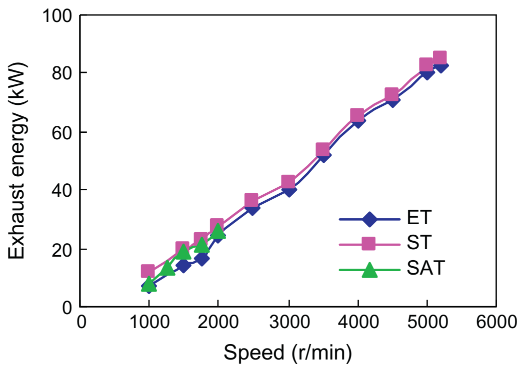


Fig. 15. IC engine exhaust gas energy.

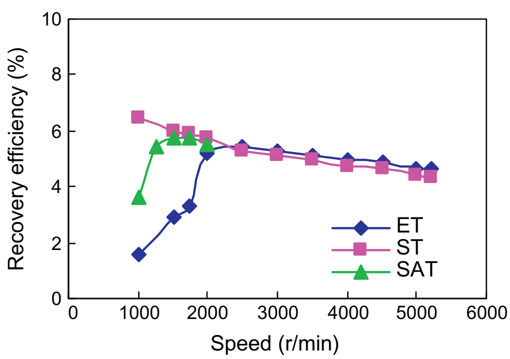


Fig. 16. IC engine exhaust gas energy recovery efficiency.

including low exhaust gas pressure, low mass flow rate of exhaust gas and low turbine efficiency.

5. Conclusions

Through the above analysis, the following conclusions could be arrived.

(1). Exhaust turbocharging is a kind of direct method for IC engine exhaust gas energy recovery. At the IC engine low-speed operating conditions, since the exhaust gas pressure and exhaust gas mass flow rate are very low, the expansion ratio and efficiency of turbine are influenced. As a result, IC engine cannot achieve the target boosting pressure at the low-speed. Steam turbocharging is a kind of indirect method for IC engine exhaust gas energy recovery. In the entire IC engine speed area, the output power of steam turbocharging system is much larger than the required compressor power, and the residual turbine power can be recovered by coupling a high-speed motor. Steam-assisted turbocharging is an integration mode of steam turbocharging and exhaust turbocharging. It can effectively promote IC engine intake gas pressure, and improve the low-speed performances especially the power performances.

(2). On the condition of the same intake gas pressure, the exhaust gas pressure of steam turbocharging engine is lower than that of exhaust turbocharging engine. As a result, the PMEP and BMEP of steam turbocharging engine are higher than exhaust turbocharging engine. Steam-assisted turbocharging can enhance both the intake gas pressure and exhaust gas pressure. Because the intake gas pressure plays a leading role, both the PMEP and BMEP of steam-assisted turbocharging engine can be improved. However, the improvement of steam-assisted turbocharging is lower than steam turbocharging.

(3). On the premise that intake gas pressure reaches a certain level, e.g. target boosting pressure of 1.5 bar, the thermal efficiency of exhaust turbocharging engine is higher than the original naturally aspirated engine. In the entire speed range, both the steam turbocharging engine and steam-assisted turbocharging engine have higher thermal efficiency than original naturally aspirated engine and exhaust turbocharging engine, while the steam turbocharging engine has higher energy saving potential. At 5000 r/min, the thermal efficiency of steam turbocharging engine has an increase of 3.6% points over the original naturally aspirated engine.

(4). When the IC engine speed is lower than 2000 r/min, steam turbocharging has higher exhaust gas energy recovery efficiency than the other two kinds of boosting pressure approaches, and the maximum exhaust gas energy recovery efficiency of steam turbocharging is 6.5%. The exhaust gas energy recovery efficiency of steam-assisted turbocharging is higher than exhaust turbocharging but lower than steam turbocharging, and its maximum value is 5.7%. Owing to the low exhaust gas pressure, low exhaust gas mass flow rate and low turbine efficiency, the exhaust gas energy recovery efficiency of exhaust turbocharging is the lowest at the low-speed operating conditions. When the IC engine speed is higher than 2000 r/min, intake gas pressure of exhaust turbocharging engine can reach the target value. In the meantime, the exhaust gas energy recovery efficiency of exhaust turbocharging is approach to that of steam turbocharging, and both of them decrease with the increasing of IC engine speed.

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